WOODS HOLE OCEANOGRAPHIC INSTITUTION

Applied Ocean Physics and Engineering Department, Woods Hole, MA 02543-1053

April 22, 2014

Dr. Thomas F. Swean
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

Dear Dr. Swean:

Enclosed is the final report for ONR grant N00014-07-1-0135 entitled "Full-Scale Measurement and Prediction of the Dynamics of High Speed Helicopter Tow Cables with Hard-Nose Fairings", Principal Investigators Drs. Michael Triantafyllou and W. Rockwell Geyer.

Please let me know if you need further information.

Sincerely,

Shirley Barkley

Shirley Barkley
Administrative Associate II

Enclosures

cc: Administrative Grants Officer
Naval Research Laboratory
Defense Technical Information Center
WHOI Grant & Contract Services
AOPE Department Office

FINAL REPORT

Full-Scale Measurement and Prediction of the Dynamics of High-Speed Helicopter Tow Cables

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February 14, 2014

LONG-TERM GOALS

To provide the Navy with a non-invasive measurement technique and a numerical simulation tool for analyzing the vibration response of high-speed towed cables using a helicopter. The non-invasive measurement technique is based on fiber Bragg gratings, which measure the tensions and transverse vibrations of a high-speed tow cable at multiple sites along the cable. The numerical tool is based on combining two software applications, WHOI CABLE for calculating tow cable shape and an updated version of MIT's VIVA for calculating hydro-elastic multi-mode vibration response and variable drag coefficient of a cable in arbitrary current.

OBJECTIVES

To construct and test in at sea trials a prototype electro-optical test cable with the same dimensions as that of the OAMCM tow cable. We are using the test cable to demonstrate, through full-scale measurements, that fiber Bragg gratings can measure the vibrational amplitudes and frequencies along the length of the cable under high speed towing conditions. The results from the full-scale measurements are used to verify the numerical simulation tool for predicting tow cable strumming and flutter. A numerical simulation that accurately models these processes will increase NSWC's ability to design tow cables with the proper distribution of ribbon and hard-nose fairing and to do mission planning. In addition, we are developing alternative designs to suppress strumming and at the same time avoid galoping and significant side curvatures.

APPROACH

For the first goal of the project, our approach to developing a vibration measurement technique is to use a ship-towed cable system that captures the dynamic effects of the in-water portion of the OAMCM system. We are using a 100 m long and 13 mm diameter tow cable with a 250-kg and 1000-

kg tow vehicle in order to vary angles of inclination. We conduct tests with bare cable, an all-ribbon-faired cable, and one that has a combination of ribbon fairing and hard-nose fairing at tow speeds up to 17 knots. The technique for measuring vibration amplitudes along the cable is based on fiber Bragg grating (FBG) sensors (Othonos & Kalli, 1999). Multiple gratings are constructed along the cable by etching a small region of an imbedded optical fiber with periodic bands of high and low refractive index. The grating spacing is typically between 500-550 nm, and the total length of a single grating is usually 0.1 to 2 cm long. As light propagates through a FBG, it is partially reflected at each interface between the bands of high and low refractive index. If the spacing between the bands is constant such that all the partial reflections add up in phase for a particular wavelength—i.e. when the round trip of the light between two reflections is an integral number of a given wavelength—the total reflection can grow to nearly 100%, even if the individual reflections are very small. This condition will hold for a specific wavelength of light called the Bragg wavelength λ_{Bragg}. For all other wavelengths, the out-of-phase reflections cancel each other, resulting in low reflection. As the cable vibrates, the spacing between the bands will change slightly, which can be measured by a change in the Bragg wavelength. State-of-the-art FBG interrogators can resolve Bragg wavelength shifts down to 0.001 nm, which corresponds to a strain of about 1 $\mu\varepsilon$. Vandiver *et al.* (2006) used Bragg gratings to record bending strains due to strumming of a flexible cylinder and easily measure strains down to 10 $\mu\varepsilon$. Our own tests show that we can resolve a regular sinusoidal dynamic strain of amplitude ± 1 $\mu\varepsilon$.

For the numerical simulation, we develop appropriate vibration models and incorporate them into our WHOI Cable software (Gobat & Grosenbaugh, 2006). The vibration models will be based on MIT's VIVA software (Triantafyllou et al., 1999). VIVA predicts the vibrations of flexible cylinders (including marine cables and offshore risers) by assuming a harmonic response consisting of complex modes whose amplitude and phase vary along the cylinder length. The program permits standing waves, traveling waves, and a combination of the two. Different regions along the cylinder can produce or dissipate energy depending on the flow conditions. Production and dissapation are modeled with hydrodynamic coefficients that are based on the local flow velocity and the local vibration response (i.e. the non-dimensional vibration frequency and amplitude). The frequency of the oscillating hydrodynamic force is assumed to be equal to the frequency of the cable vibrations. The hydrodynamic force is decomposed into two components: one component in phase with the acceleration (represented by the added mass coefficent C_m) and one component in phase with the velocity (the lift coefficient in phase with velocity), which can be either an excitation ($C_{Lv} > 0$) or a damping force ($C_{Lv} < 0$). Experimental tow-tank data are used to establish the magnitude of the hydrodynamic coefficients as a function of the vibration response. For this project, tow tank testing is being used to enhance the database for bare cables, and new data is being collected for ribbon-faired cables and cables with hard-nose fairing.

TASKS COMPLETED

Per the original proposal all tasks were completed, including laboratory tests at the Towing Tank, field tests and implementation of the hydrodynamic tests to the numerical codes. Two appendices provide technical information on the field tests (Appendix A) and the Towing Tank tests (Appendix B).

1. Towing Tank tests

Three sets of towing experiments were performed to model the forces on a vertical piece of straight cable outfitted with TufNose® fairings: 1) zero cross-flow motion at fixed angle of attack, 2) forced cross-flow motion with fixed angle of attack, and 3) forced cross-flow motion with free rotation. Fig. 1 shows a picture of the TufNose® fairings used in experiments. In experiments with fixed motion and fixed angle of attack, the fairings are towed through water with the fairing held at a specific angle of attack. The static lift and drag forces on the fairings are measured in this configuration. In experiments with forced motion and fixed angle of attack, the fairings are again held at various angles of attack, while the fairings are forced to move within a range of tranverse amplitude A and reduced velocity V_r matrix. The angles of attack are varied from 0 to 30 degrees at 5-degree increments.

Experiments were performed in order to characterize the behavior of the fairings at an angle of inclination and so as to predict potential vibration problems due to fairing inclination. The inclined cable experiments involved mounting the model with fairings on a mount, which can vary the angle of

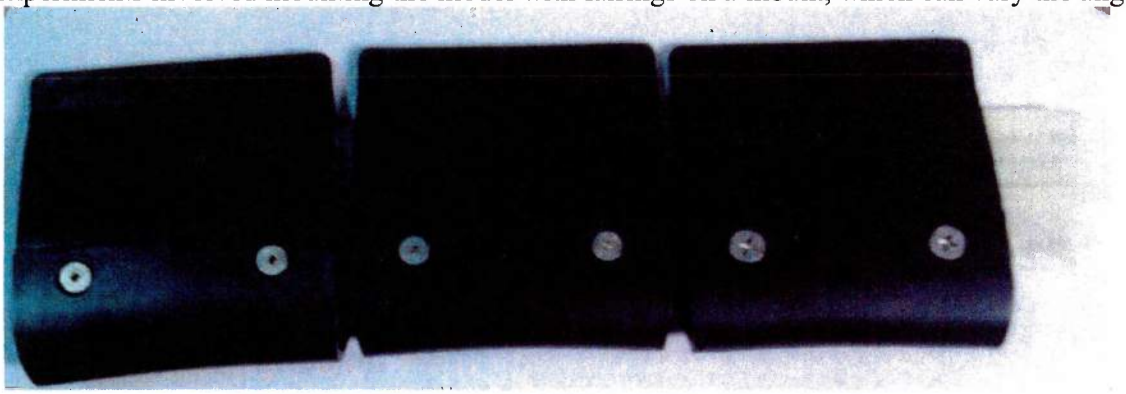

Figure 1: Tuff-Nose fairings.

inclination of the fairings. The same types of experiments as in the previous fairing tests were performed, with fixed angle of attack, fixed angle of attack with force heaving motion, and free rotation. With each of these sets of experiments, the inclination angle was varied between 0 and 45 degrees in increments of 15 degrees. The angle of attack was limited to between 0 and 30 deg., at increments of 15 degrees.

A set of experiments using curved rods was designed to investigate the force coefficients on fairings allowed to freely rotate on a curved rod. The maximum curvature allowed by the fairings was determined by measuring the curvature of the fairings in a curved orientation. The maximum curvature is defined as the point where the fairings begin to touch one another. Additional curvatures were tested based on percentages of the maximum curvature. Fig. 2 shows the curved rods with fairings used in the experiments. The three curvatures used were 100% max curvature, 80% max curvature, and 60% max curvature. All of the curvatures used are based on the radius of a circular arc. In real applications, the curvature will certainly be more complex than a circular arc, but this definition is used to standardize the tests in the lab. It is important to note that the curvature of the rod is completely defined within the plane of the fairings, in the direction of the fluid flow. There was no three dimensional curvature in the test rods. In the curved configuration, the fairings are allowed to rotate freely around the curved rod. The fairings are then towed forward and forced motions are applied as in previous experiments.

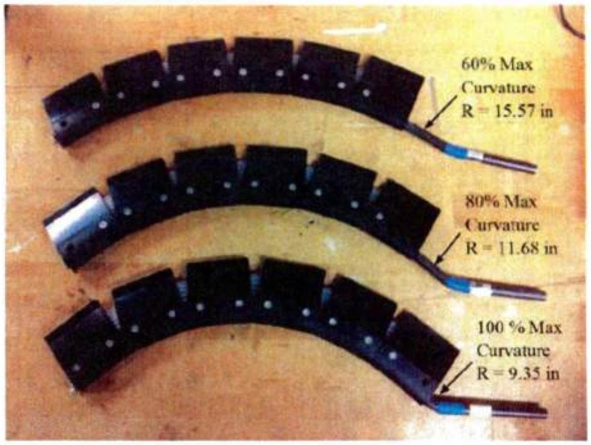

Figure 2: Curved Rods with fairings. Three curvatures used in testing.

2. Results of the Towing Tank tests

When the fairing is free to rotate, the fairings appear to work well and there is no noticeable excitation region within the range of motions tested. However, if the fairing is fixed at any angle of attack, an excitation region exists with positive C_{Lv}. In general, as angle of attack increases, the excitation region increases. A series of figures was created that maps C_{Lv} as a function of A, V_r, angle of attack.

Increasing the inclination angle has a similar effect to increasing angle of attack. The excitation region grows with increasing inclination angle. This would imply that if the fairings become fixed in orientation, significant inclination of the cable may help excite VIV, even for small angles of attack. When the fairing is free to rotate at various inclination angles, the fairings behave as designed and align to the flow properly. There is no excitation region observed in this orientation. However, for all other inclination angles, positive excitation is possible over a large range of reduced frequencies. It must be noted that at the slow towing speeds of the experiments (U = 0.2 m/s), the drag acting on the fairing was not able to overcome the effect of gravity on the fairing. This caused the fairing to sag, so the fairing did not always align to the flow properly. It is expected that in full-scale tests to performed later this year, the tow speed would be much higher and the fairing would be able to align with the flow properly. It must be noted, however, that in transient conditions at the start of towing or in maneuvering, it is possible that the tow speed will decrease significantly and the fairings could sag due to inclination of the cable. This would possibly induce vibrations of the cable. The inclination angle was also varied to determine its effect on lift and drag on the static fairing. As before, a series of figures was created that maps C_{Lv} as a function of A, V_r, angle of attack.

It was observed that significant curvature of the cable can cause significant problems for the fairings. It was found that for all curvatures tested, even when the fairings were not restricted from rotating on the curved rod, the fairings were unable to rotate in order to align with the flow on any of the curved rods. This problem was worse for the higher curvatures and at 100% max curvature, the fairings were essentially fixed in place. At 60% max curvature, there was still some allowed movement on the fairings, but only about 20 degrees in each direction. The inability to rotate on the curved rod stems from multiple problems with the fairings. Since each fairing is attached to the next fairing with a plastic joining piece, the fairings on the curved rod are all joined together. When the fairings then try to rotate on the curved rod, they experience a curvature on the rod that is not in the direction of curvature allowed by the fairing connections. The fairings then lock in place and are unable to rotate completely around the curved rod. It was hypothesized that by disconnecting the fairings from one another, the fairings may be able to rotate individually around the curved rod, however this was not the case.

Figs. 3 and 4 show an individual fairing on a piece of curved rod. In Fig. 3, the fairing is located on a straight section of the rod. In this case, the fairing can easily rotate completely around the rod. In the picture, the fairing aligns with gravity. In Fig. 4, the fairing is moved slightly to a position on the rod where there is slight curvature. The fairing will easily slide onto the rod if the fairing is aligned with the direction of curvature, however, the fairing can no longer rotate completely around the rod. Fig. 4 shows that with the rod in the same orientation as Fig. 3, yet the fairing is unable to align with gravity. This happens because the fairing has no flexibility. The region of the fairing that attaches around the cable is therefore a straight tube, barely larger than the cable itself. When the fairing tries to rotate, if there is enough curvature in the cable, the individual fairing will become stuck.

Figure 3: Single fairing on curved rod. Fairing is on straight section of rod and easily aligns in the direction of gravity.

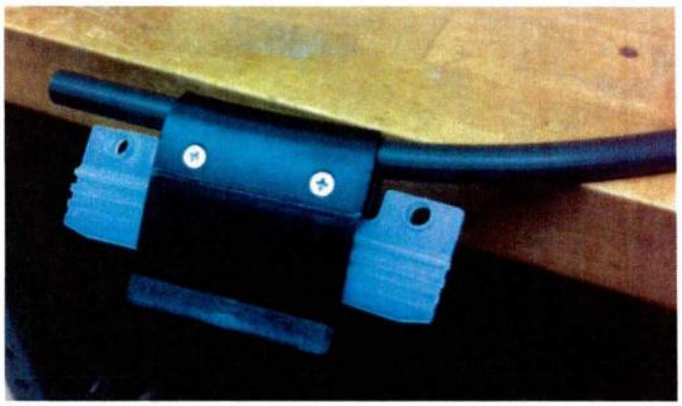

Figure 4: Single fairing on curved rod. Same fairing as in Fig. 2 is on the same rod, but is moved into a region of slight curvature. Fairing is unable to align with gravity.

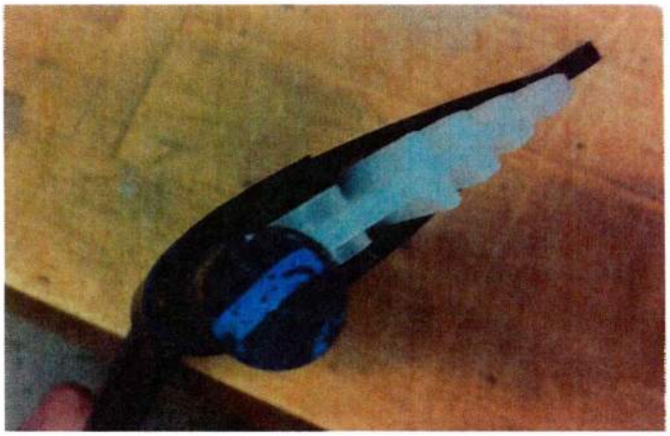

Figure 5: Bottom view of single fairing on curved rod. The fairing is unable to rotate on the curved rod because the width of the cable hole in the fairing cannot accommodate the additional width from local curvature of the rod.

Fig. 5 shows a bottom view of a single fairing on the curved rod in a stuck position. One can see in this image that the hole in the fairing, through which the cable passes, is not large enough to accommodate curvature in the rod. The problematic dimension is the width of the hole. The hole isslightly larger in length, which explains why the cable can easily slide onto the curved rod, or easily conform to curvature in a straight plane on a cable. Since the hole is large in the chord length direction, the fairing can accommodate curvature of a cable, where the curvature is in the same direction as the flow velocity. The problem is that if the curvature of the cable remains in a straight plane, but the fairing needs to align to flow that is not in the direction of the curvature, the fairing will be unable to rotate since the width of the hole in the fairing is not large enough to accommodate for out-of-plane curvature. Therefore, the fairing becomes stuck in a particular orientation.

On a real cable, the cable has the ability to flex more than the rigid rods that were used in testing, so it is possible that if the flow direction changes, the curvature of the cable will change to align with the flow direction. In practice, however, the cable should be under high tension, so it is unlikely that significant flexure would occur immediately to accommodate rotation of the fairings in order to align to the incoming flow. Additionally, these initial findings would indicate that if there is any slight 3-D curvature to the cable, this could easily cause the fairings to become stuck in a particular orientation. Previous test have already shown that if the fairings become stuck at an angle of attack, significant vibrations may occur.

In the practice of utilizing the fairing, the problem of out-of-plane curvature seems to be unavoidable. For initial transients in first starting to tow the cable, the cable would likely experience out-of-plane curvature. Similarly in maneuvering, the cable is likely to experience out-of-plane curvature. Even in a steady towing situation, it is likely that there would be some heading fluctuation of the towing vehicle, in which there would be some out-of-plane curvature experienced by the cable. These initial observations indicate that even for very minor curvature of the cable, the fairings would be unable to align to the flow properly. Problems with the force sensing equipment rendered results from the curved fairing experiments unusable. These are being repeated later this year. However, since the fairings were unable to rotate and align with the flow, it is expected that the force coefficients associated with curvature on the cable would be similar to the force coefficients for the fairing with fixed 0 degree angle of attack at incline.

2. Field Tests

We conducted field tests off the coast of Woods Hole, MA, using the WHOI ship R/V Tioga and the instrumented cable fitted with the fairings. We used a 45 m section, of which 25 m was bare cable and 20 m were outfitted with Odim Spectrum TufNose fairings, and the tests were conducted in the Woods Hole Oceanographic Institute Buoy Farm off the southern coast of Massachusetts, in order to achieve proper depths without risking impact with the ocean floor.

The R/V Tioga was used as the test platform, a 60 ft long, aluminum hulled research vessel capable of speeds up to 20 knots and featuring an A-frame and a platform with a winch. A 0.55 in diameter braided steel cable was outfitted with the fairings. The cable featured three fiber optic cables with 8 Bragg gratings on each cable for analyzing changes in tension in the cable. The fiber optic cables ran down the center of the 150 meter long steel cable. Fairings were only placed on 20 meters of the cable due to limitations of the achievable forces on the winch and A-frame of the R/V Tioga. The tested portion of cable consisted of a 576 lb tow body connected to the end of the steel cable, 5 meters of bare cable, then 20 meters of cable with Tufnose fairings, followed by 20 more meters of bare cable. The tow body was connected to the steel cable with a shackle. The connection point of the cable to the tow body was initially located at the center of tow location, 3 inches forward of the fore/aft center of gravity of the body. Tests were also performed with the tow body connected at the forward-most tow location, which was 6 inches forward of the fore/aft center of gravity of the body. The center of gravity of the tow body was located 23.56 inches aft of the nose of the body, at the aft-most tow location. The installation of the Tufnose fairings requires that adjacent fairings to be connected with clear, rigid plastic connections, such that adjacent fairings will align with the flow as a rigid body. Fairings were rigidly connected in this manner over 10 foot sections on the cable and anti-stacking rings were placed between each of the 10 foot sections in order to keep fairings from being able to slide up and down the cable.

Once the cable was deployed, measurements were initially made with no forward speed to document base strain on the cable. Using the middle tow point on the tow body, the cable was towed at increasing increments of 4 knots to observe the response of the cable (4, 8, 12, and 16 knots). An attempt was made to reach 20 knots, however drag on the cable and tow body was too large at this speed and the tow body surfaced, such that the cable was no longer submerged. The tow point was moved to the forward most towing point in an attempt to stabilize the tow body and tests were performed at 4, 8, and 12 knots in this configuration. A test was also performed at 11 knots in which 20 additional meters of bare cable were deployed under speed in an attempt to drive the cable deeper.

Professor Jason Dahl of the University of Rhode Island conducted the tests and processed the data.

Figure 6 shows the view from the stern of the ship at a towing speed of 4 knots when no kiting or other instabilities are noticeable.

Figure 6: Towing of the cable with fairings at a speed of just under 8 knots. Straight towing is possible without instabilities. WHOI ship R/V Tioga.

Once the towing speed exceeds 8 knots, the curvature of the cable due to quasi-static hydrodynamic loading exceeds the threshold value that will cause adjacent fairings to have significant inter-frictional forces. As a result, some of the fairings are "stuck" in a non stream-aligned position, or even undergo plastic deformations. As shown in Figure 7, this causes the development of a side lift force, and hence "kiting", an unstable behavior of the towed cable, developing large lateral motions, either to one side or the other. This phenomenon is predicted by the software when the hydrodynamic data from the Towing Tank tests are employed; and was clearly shown in the field tests.

As Figure 7 shows, once a speed of 8 knots was reached, the cable was kiting to one side, a clearly undesirable effect of the fairings being unable to straighten with the flow. Towing in a straight line was impossible, even with corrective action taken from the boat.

Figure 7: Towing of the cable with fairings at a speed of 8 knots, which resulted in significant kiting to the right of the viewer. Straight towing was impossible.

At an even higher speed of 12 knots, severe kiting developed, as shown in Figure 8. Kiting could develop either to the left or to the right, demonstrating that it was caused by the inter-fairing friction and the buckled-like form of the fairings. Kiting was significantly more severe than at lower speeds and the cable could move from one side to the other.

Inspection of the cable at the conclusion of the tests showed clearly the effects of friction caused by large curvature. As shown in figure 9, fairings have signs of plastic deformation, resulting in large uneven gaps at the leading edge of the fairings and uneven edges where one fairing touches another.

Figure 10 shows the towed vehicle that was used to stabilize the end of the faired tether. Stabilization was impossible beyond a speed of 8 knots, demonstrating the importance of developing curvature-tolerant fairings or alternative means of VIV cancellation, to avoid directionality effects and kiting.

Figure 8: Towing of the cable with fairings at a speed of 12 knots, resulting in severe kiting to the left of the viewer. Straight towing was also impossible, while unstable kiting was also observed.

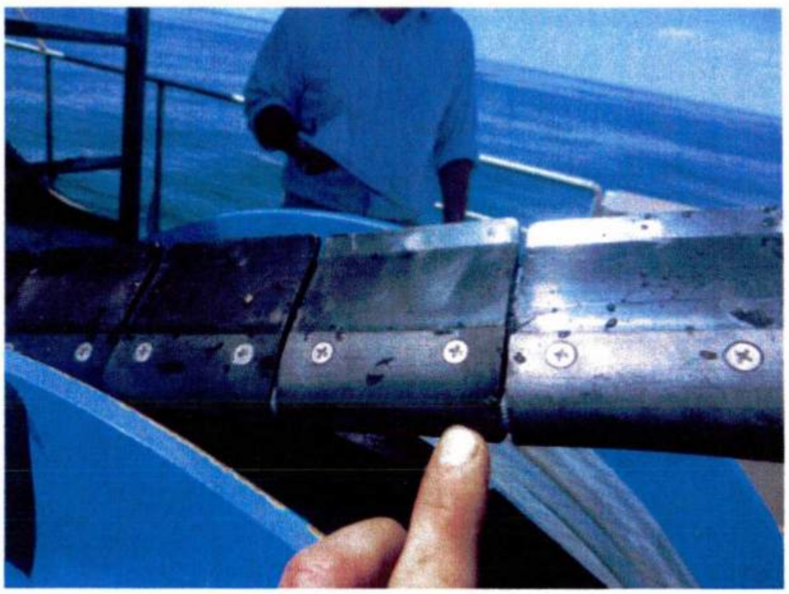

Figure 9: Inspection of the cable following the experiments clearly demonstrates the strong frictional forces and plastic deformations developing during towing as a result of the large static curvature due to the hydrodynamic drag. Fairings shown were 180 degrees out of line with respect to the other fairings.

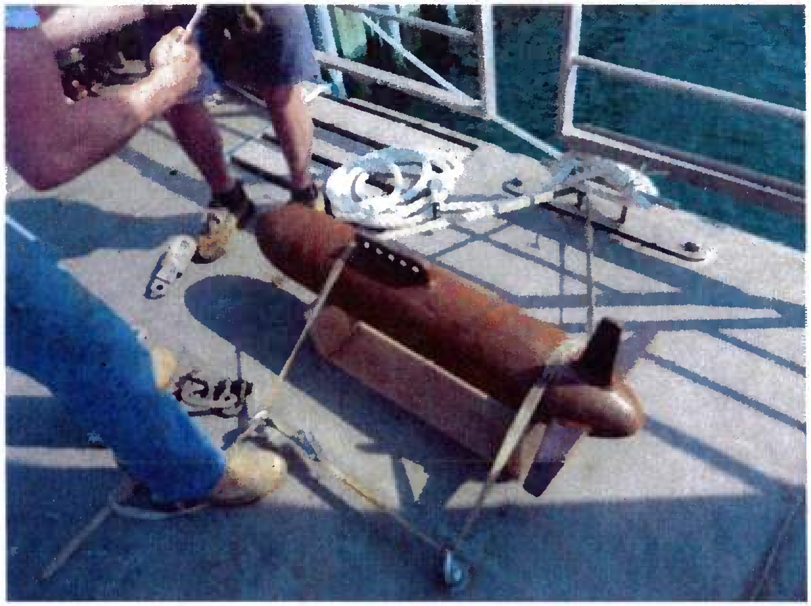

Figure 10: 250 kg towed vehicle to stabilize the end of the towed tether with fairings. Stabilization was impossible beyond a speed of 8 knots, due to kiting.

3. Development of alternative procedures

We have tested fairings with special cuts in their configuration, so as to reduce the inter-fairing frictional forces, as described in the section on Towing Tank testing. In simulation, using the hydrodynamic data from the experiments, we predict that higher speeds can be achieved than with conventional fairings – reaching speed of the order of 14 knots. However, the desirable speed of over 20 knots is still not feasible due to curvature effects.

We have looked at alternative ways of reducing VIV, which do not employ fairings, including biomimetic VIV cancellation by spanwise modulation of the section. If these tests prove feasible, alternative towing arrangements will be proposed.

IMPACT/APPLICATIONS

NSWC in Panama City is currently working to overcome issues directly related to the mechanical strength of the OAMCM tow cable and its terminations. Our research focuses on the hydrodynamic towing characteristics and improvements to the fairing system that mounts on the cable. Eliminating cable vibrations due to flutter and strumming will ultimately improve the mechanical performance through the reduction of fatigue. Our numerical simulation will provide tool for predicting vibration and cable drag that can be used for design and mission planning. Our fiber Bragg grating sensors provide us with the means for verify our numerical simulation and, in the future, could provide the Navy with a non-invasive tool for monitoring the performance of the OAMCM tow cable during actual missions.

TRANSITIONS

We continued to make our *WHOI Cable* software available to academic institutes, government research labs, and government contractors at no cost through our FTP site. At present, nearly 200 different individuals, including a number of engineers working at Navy Labs and on Navy funded R&D projects, use *WHOI Cable* for mooring and tow cable analysis. Our new version includes VIVA and an updated user interface.

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Appendix A: TufNose Fairing Tests on R/V Tioga at WHOI

Jason M. Dahl, University of Rhode Island

1 Experimental Description

Field tests were performed on a 45 m long cable outfitted with Odim Spectrum TufNose Fairings. Tests were performed in the Woods Hole Oceanographic Institute (WHOI) buoy farm off the southern coast of Massachusetts in order to achieve appropriate cable depths without risking impact with the ocean floor. The R/V Tioga was used as the test platform, a 60 foot long, aluminum hulled research vessel capable of speeds up to 20 knots and featuring an A-frame and platform for a winch.

A 0.55 inch diameter braided steel cable was outfitted with the fairings. The cable featured three fiber optic cables with 8 Bragg gratings on each cable for analyzing changes in tension in the cable. The fiber optic cables ran down the center of the 150 meter long steel cable. Fairings were only placed on 20 meters of the cable due to limitations of the achievable forces on the winch and A-frame of the R/V Tioga. The tested portion of cable consisted of a 576 lb tow body (see appendix) connected to the end of the steel cable, 5 meters of bare cable, then 20 meters of cable with Tufnose fairings, followed by 20 more meters of bare cable.

The tow body (see appendix for dimensions) was connected to the steel cable with a shackle. The connection point of the cable to the tow body was initially located in the center tow location, 3 inches forward of the fore/aft center of gravity of the body. Tests were also performed with the tow body connected at the forward-most tow location, which was 6 inches forward of the fore/aft center of gravity of the body. The center of gravity of the tow body was located 23.56 inches aft of the nose of the body, at the aft-most tow location.

The installation of the Tufnose fairings requires that adjacent fairings to be connected with clear, rigid plastic connections, such that adjacent fairings will align with the flow as a rigid body. Fairings were rigidly connected in this manner over 10 foot sections on the cable and anti-stacking rings were placed between each of the 10 foot sections in order to keep fairings from being able to slide up and down the cable.

APPENDIX B

EXPERIMENTS TO ESTABLISH THE HYDRODYNAMIC DATABASE FOR TOWED CABLES WITH FAIRINGS AND RIBBON FAIRINGS, STRAIGHT, OR INCLINED, OR CURVED

M.S. Triantafyllou, J. Dahl, Y. Modarres-Sadeghi, H. Zheng, Sam Roberts, Robert Allen

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